Borrmann Effect in Photonic Crystals: Nonlinear Optical Consequences

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Nonlinear-optical manifestations of the Borrmann effect that are consequences of the spectral dependence of the spatial distributions of the electromagnetic field in a structure are observed in one-dimensional photonic crystals. The spectrum of the light self-focusing effect corresponding to the propagation-matrix calculations has been measured near the edge of the photonic gap.

Photonic crystals, i.e., microstructures with the periodic modulation of the refractive index that have a photonic gap, are actively studied [1], [2]. Various nonlinear optical effects such as the generation of the second- [3], [4] and third-optical harmonics [5] and self-action (self-focusing) radiation effects [6] were observed in photonic crystals.

The Borrmann effect is the anomalous transmission of x-rays due to the spectral dependence of the spatial distribution of the electromagnetic field in a crystal. This effect was observed in quartz [7]; more recently, a similar phenomenon was observed in calcite crystals [8]. The anomalous transmission was explained by von Laue [9]: since a crystal body is a periodic atomic structure, the eigenmodes of the electromagnetic field in an x-ray range are standing waves. For various wavelengths, the antinode of a standing wave can be either on an atom or between the atoms. In the latter case, the absorption of light in the substance is much lower and, correspondingly, the transmittance of x-ray radiation is anomalously high.

It can be assumed that the Borrmann effect should be observed in photonic crystals. According to the optical analog of the Bloch theorem, the solution of the wave equation in a structure with a periodically varying refractive index is a plane wave modulated in amplitude with a period coinciding with the modulation period of the refractive index. Thus, the spectral dependence of the optical field in a one-dimensional photonic crystal in the direction perpendicular to the layer plane has nodes and antinodes whose mutual arrangement certainly depends on the wavelength of the incident radiation. By varying the wavelength (or the angle of radiation incidence for one-dimensional photonic crystals), one can shift the antinodes of the standing wave from optically denser layers to optically less dense layers and observe modifications of various nonlinear optical effects. In particular, if the nonlinear optical susceptibilities of the photonic crystal layer are significantly different, the magnitude of the nonlinear optical effect depends on the type of layers in which the antinodes of the standing light wave appear inside the photonic crystal.

The self-action of light is a process based on change in the refractive index of the substance under the action of an intense light field. The radiation self-focusing effects are quite well studied for the propagation of intense Gaussian light beams [10]. The electromagnetically induced addition to the refractive index in the self-focusing effect is quadratic in the field, $\Delta n \backsim \chi^{(3)}_{(\omega=\omega+\omega-\omega)}|E_\omega|^2$, where $\chi^{(3)}$ is the third-order nonlinear susceptibility tensor and E_ω is the electric field strength of the probe radiation. This effect was taken for the visualization of the Borrmann effect, because it is insensitive to the phase of the interacting waves in contrast to, e.g., the generation of harmonics. Thus, the Borrmann effect in a nonlinear photonic crystal formed by alternating linear and nonlinear layers should be manifested in the spectral dependence of the self-focusing effect magnitude.

The aim of this work is to observe an optical analog of the Borrmann effect in nonlinear photonic crystals using the nonlinear self-action method. The photonic crystal samples were produced by magnetron sputtering. A photonic-crystal mirror that is a one-dimensional photonic crystal consisting of six bilayers 96-nm bismuth-doped yttrium iron garnet (Bi:YIG) and 149-nm silicon oxide SiO_2 - is deposited on a fused-silica substrate. The optical thickness of each component of a bilayer is $\lambda/4$, where $\lambda \simeq 870$ nm is the central wavelength of the photonic gap. The third-order nonlinearity of yttrium iron garnet in the optical and near IR ranges is much higher than that of the silicon oxide layers [11]. The measured transmission spectrum of the structure is shown in the inset in Fig. 1a.

The distribution of the electric field in the above structure was calculated using the propagation-matrix method [12]. The typical distributions of the electric field squared $|E_\omega|^2$ inside the structure at the radiation wavelength near the spectral edges of the photonic gap are shown in Fig. 1b, where the spatial distribution of $|E_\omega|^2$ in the structure is shown, because the light selffocusing effect investigated in the experiment is proportional to this quantity.

The radiation localization degree in layers of each type is determined by summing $|E_\omega|^2$ over 30 points in each layer. The distributions of $|E^L_\omega|^2$ and $|E^{NL}_\omega|^2$, where $|E^L_\omega|^2$ and $|E^{NL}_\omega|^2$ characterize the radiation intensities in the linear (SiO_2) and nonlinear (Bi:YIG) layers of a

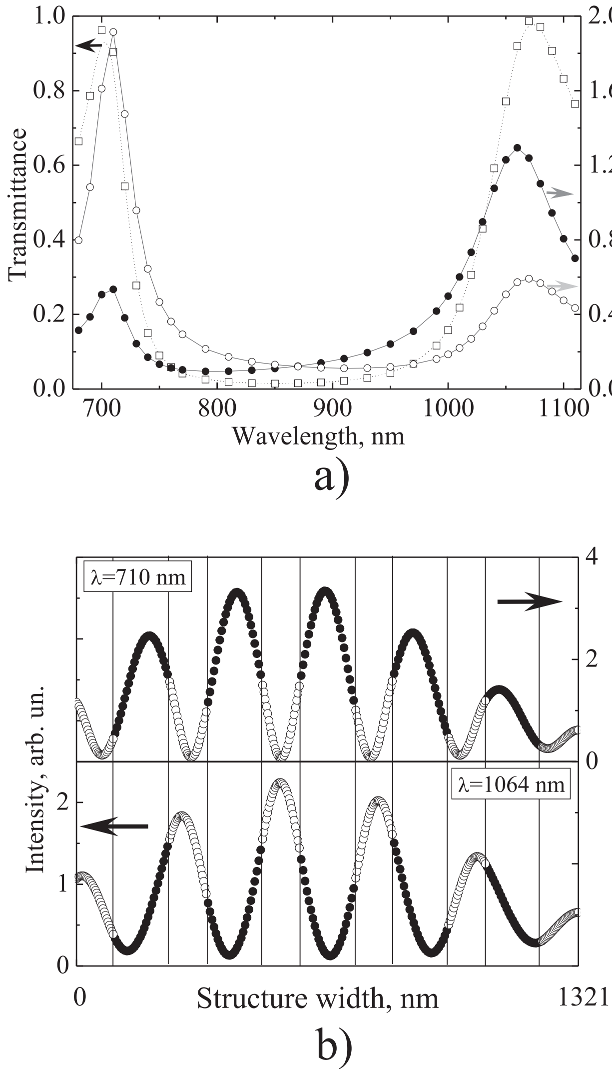

Figure 1: (a) (Open squares, dotted line) Transmittance spectrum of the photonic crystal and the calculated intensity of the optical field localized in (open circles) linear and (closed circles) nonlinear layers of the photonic crystal. (b) The spatial distribution of the optical field squared in the (closed circles) linear and (open circles) nonlinear layers of the photonic crystal for a wavelength of (upper panel) 710 and (lower panel) 1064 nm as calculated using the propagation matrix method.

photonic crystal, respectively, were obtained in this way. Figure 1a shows the spectral dependences of the radiation intensities $|E_\omega^L|^2$ and $|E_\omega^{NL}|^2$ in the wavelength range covering the photonic gap and its both edges. It is seen that light at the (upper panel, Fig. 1b) short- and (lower panel, Fig. 1b) long-wavelength edges of the photonic gap is predominantly localized in the linear and nonlinear layers of the photonic crystal, respectively.

The relative radiation intensity $|E_\omega^{NL}|^2$ is nonmonotonic and has a maximum near the long-wavelength edge. The intensity $|E_\omega^L|^2$ has a maximum near the short-wavelength edge. The intensity in the center of the

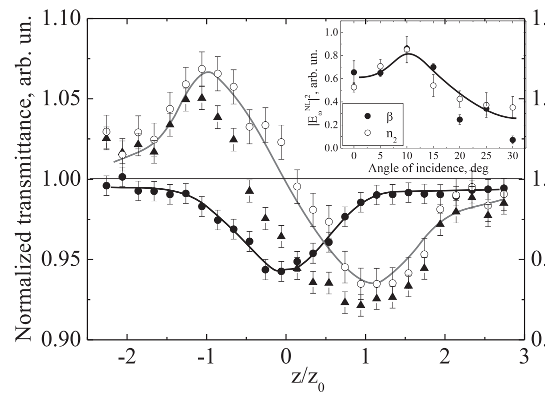

Figure 2: Effective transmittance for the cases of the (closed circles) open diaphragm, (closed triangles) closed diaphragm, and (open circles) their ratio. The inset shows the angular dependence of the intensity of the radiation localized in the nonlinear layers of the photonic crystal, $|E_\omega^{NL}|^2$. The open and closed circles are determined from the selffocusing and two-photon absorption data, respectively.

photonic gap is equally distributed between the linear and nonlinear layers. The spectral vicinity of the long-wavelength edge of the photonic gap is nonmonotonic and has a maximum.

The z-scan method was used to analyze the cubic self-action effects at the probe radiation wavelength. The method proposed in [13] is similar to that used in [6]. Radiation from a Nd^{3+} laser (a wavelength of 1064 nm, a pulse duration of 15 ns, a repetition rate of 25 Hz, and a pulsed power density up to 10 MW/cm^2) was focused on a sample by a lens with a focal length of 6 cm. By means of a translator, the sample is displaced along the beam-propagation direction near the focal plane of the lens, allowing one to control the radiation power density on the sample.

When the self-focusing effect is investigated, radiation passed through the photonic crystal fell on a limiting diaphragm and an IKS-1 filter and was detected by a UPD-70-IR2 photodiode. The effective transmittance of the aperture receiver was measured in the experiment as a function of the sample position with respect to the lens focus, $T(z)$, where $T(0)$ is the transmittance of the sample located near the focal plane of the lens and $T = 1$ is the T value for the sample located far from the lens focus. The nonlinear (two-photon) absorption was measured similarly, but the diaphragm in front of the photodiode was in the open position.

Figure 2 shows the effective transmittance for z-scan in the cases of the open and closed diaphragms. To take into account the influence of absorption on the self-action effect in the case of the closed-aperture z-scan,

the effective transmittance was normalized over the absorption curve [13]. The normalization result having a typical shape of the closed-aperture z-scan is also shown in Fig. 2. Similar measurements were carried out at the angles of incidence from 0 to 30, corresponding to wavelengths from 1064 to 1090 nm. The typical n_2 values ($\Delta n = n_2 I$, where I is the radiation intensity) in this spectral range were $(3\div7)\cdot10^{-8}$ cm^2/W, which are higher than a similar value for magnetophotonic microcavities with the: $(Ti_2O_5/SiO_2)^5$/Bi:YIG/$(Ti_2O_5/SiO_2)^5$ structure [6]. Assuming that the nonlinear susceptibility $\chi^{(3)}_{(\omega=\omega+\omega-\omega)}$ and two-photon absorption coefficient β are constant in this spectral range, we determine the relative $|E^{NL}_\omega|^2$ values from the $T(z)$ dependencies obtained for the self-focusing and two-photon absorption effects in this spectral range.

The angular spectrum of the nonlinear optical effects (proportional to the pump-field intensity I^{NL}_ω) is recalculated to the frequency spectrum by means of the formula $\lambda = \lambda_0(1 - n^{-2}_{YIG} sin^2\theta)^{1/2}$. The magnitude of these effects depends on the spatial distribution of the radiation intensity inside the structure and on the transmittance of the photonic crystal: $\Delta n = n_2 I^{NL} \propto |b(\lambda)|^2 \cdot T(\lambda)$, where $b(\lambda)$ is the Borrmann coefficient characterizing the degree of the electric field localization in the nonlinear layers of the structure: $E^{NL}_\omega = b(\lambda)t(\lambda)E^{in}_\omega$, where E^{in}_ω is the pump field at the input of the photonic crystal and, $t(\lambda)$ is the transmittance for the electric field, $|t(z)|^2 = T(z)$. Since the transmittance in the region available for measurement, i.e., at the edge of the photonic gap, varies very abruptly, the curves were normalized to the transmittance of the photonic crystal $T(\lambda)$, presented in Fig. 1. The spectral dependence obtained for the square of the absolute value of the Borrmann coefficient, $|b(\lambda)|^2$, which is proportional to $|E^{NL}_\omega|^2$, is presented in Fig. 3, where the qualitative agreement between the calculations and measured quantities is observed.

The effect of the spectral dependence of the transmittance on $|b(\lambda)|^2$ can be excluded by comparing the self-focusing and two-photon absorption values at the same transmittances of the photonic crystal, e.g., at different edges of the photonic gap. Since the edges of the photonic gap correspond to the localization of the antinodes of the standing light wave in the photonic-crystal layers of different types, the self-focusing effect at one edge (in this case, at the right edge, as seen in Fig. 1a) is much higher than a similar effect at the opposite edge of the photonic gap. In this case, the difference between the localizations of the light field in the linear and nonlinear layers of the photonic crystal at different edges of the photonic gap should be most pronounced. At the same time, the spectral dependencies of the real and imaginary parts of the refractive indices of the constituent substances of the photonic crystal should strongly affect the observed effects.

In summary, the self-focusing and two-photon absorption effects have been observed in nonlinear photonic crystals. The spectral dependence of the Borrmann coefficient, which describes the distribution of the radiation electric field in the structure, is revealed in these crystals. The experimental data qualitatively coincide with the calculated dependencies and exhibit the nonmonotonic spectral dependence of the Borrmann coefficient near the long-wavelength edge of the photonic gap.

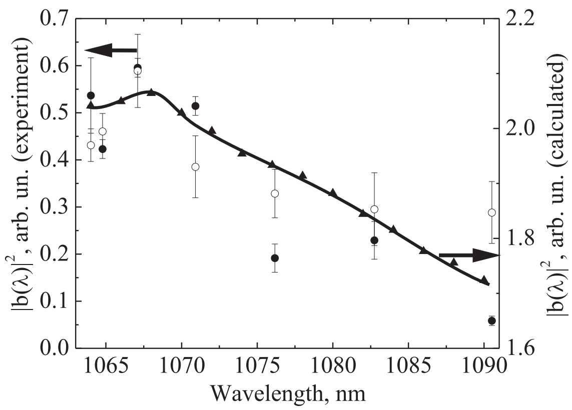

Figure 3: Spectral dependence of the Borrmann coefficient $|b(\lambda)|^2$. The closed and open points correspond to the twophoton absorption and self-focusing radiation experiments, respectively. The triangles show the calculated spectral dependence of $|b(\lambda)|^2$.

The further prospects of the investigations of the optical Borrmann effect are associated with a comparison of the nonlinear effects at different edges of the photonic gap for the same transmittance of the photonic crystal.

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